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Pulsar Electrodynamics

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Abstract. First I emphasize the magnetospheric loop current system induced by the wind activity. Next, I address the formation of the field-aligned electric field. An interesting aspect is the reaction of the inner magnetosphere to an induced current. In the traditional outer gap, the current running through the gap is all carried by the particles created in the gap. However, if external current-carrying particles are added, the gap moves inward or outward; it can even appear near the star. It is suggested that the gaps appear at various altitudes, depending on the current distribution on field lines, the field line geometry, and the source of the current-carrying particles.

For definiteness of sign of charge and current direction, $\boldsymbol{\Omega} \cdot \boldsymbol{\mu} > 0$ is assumed throughout.

1. Magnetospheric Current System

1.1. Pulsar Wind

The rotational energy of pulsars is carried off mostly by the pulsar wind. Pulsed radiation only accounts for a small fraction of the rotation power. At least for young pulsars, this idea is supported by observations of pulsar powered nebulae. *The pulsar wind is predominant in the pulsar electrodynamics.*

However, the nature of the pulsar wind is not clear. The wind is conventionally thought to be an outflow of magnetized plasmas, which transports energy in the forms of a Poynting flux and a kinetic energy flux.

Dominance of the wind may not be the case if the electromotive force of the star is marginally reduced to the voltage required for pair creation. Nevertheless, we assume dominance of the wind in the following, and this is hopefully justified for most pulsars.

1.2. Electric current in the magnetosphere

For the axisymmetric case, if there is an outflow of energy, then a simple result is a loop current system. As shown in Figure 1 (left), the current starts from the star, goes out and returns back to the star on different field lines. A DC circuit is formed, connecting the central dynamo and the load (the wind region beyond the light cylinder). The poloidal electric field produced by the dynamo and the toroidal magnetic field by the loop current make the outward Poynting flux.

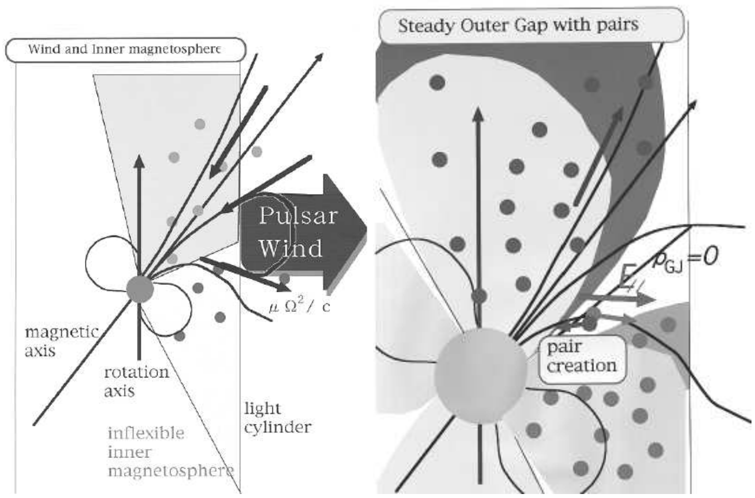

Figure 1. Left: The energy release from the magnetosphere is associated with the loop current system. Right: If pairs are created in the gap, then corotation regions expand to fill the space within the light cylinder. The associated current system is compatible with the wind activity on the left.

The current can go away to infinity and return back from infinity. However, if some part of the current closes somewhere in the outer magnetosphere, then Poynting flux is converted into the kinetic energy of the plasma to accelerate the wind ($\boldsymbol{E}\cdot\boldsymbol{j} > 0$). How much current closes in the wind is the issue whether kinetic dominant winds are formed or not. To my knowledge, this is still controversial.

For oblique cases, a non-zero displacement current complicates the interpretation. However, it can be shown that if there is *no field-aligned electric field* ($E_{\parallel} \equiv \boldsymbol{E} \cdot \boldsymbol{B}/B = 0$), the outward energy flux *does require a 'real' loop current* even with displacement current. Only for a non-vanishing field-aligned electric field ($E_{\parallel} \neq 0$) does the displacement current contribute to the outflow of energy, as in the case of magnetic dipole radiation (cf. the Appendix of Shibata & Hirotani, 1999).

An illustrative example is the oblique force-free model without field-aligned current. In this case, there is no Poynting flux across the light cylinder (Henriksen, & Norton 1975; Beskin, Gurevich, & Istomin 1993; Mestel, Panagi, & Shibata 1999)

If the potential drop associated with probable $E_{\parallel} \neq 0$ is much smaller than the available voltage, then in general, the 'real current loop' dominates in determining the rotational energy loss. As a result, the field-aligned current with an intensity of order of the Goldreich-Julian (GJ) value, is forced to run through the inner magnetosphere, connecting the generator, the neutron star, and the main load, which is the wind. This view seems to be applicable at

least for young pulsars because their electromotive force is large enough to make electron-positron pairs.

2. Constraints for the inner magnetosphere

The inner magnetosphere is *inflexible*:
(1) the magnetic field is hardly changed by the GJ current. It is essentially current free, say, dipolar.
(2) the order of strengths of various forces, i.e., pressure force $\ll$ gravitational force $\ll$ electromagnetic force, results in (i) it is the electromagnetic force that controls the particle motion; (ii) due to strong gravity, a quasi-neutral plasma cannot be supported above scale heights (a few cm). Quasi-static plasmas should be completely charge separated: plasmas are composed of either electrons only or ions/positions only; (iii) pair plasma can stay quasi-neutral only if the field-aligned electric field in it is screened out.
(3) finally the smallness of particle inertia requires the ideal-MHD condition, $\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}/c = 0$. If this applies, the particles follow the corotation plus field-aligned motion: $\boldsymbol{v} = \boldsymbol{u}_{\mathrm{c}} + \kappa\boldsymbol{B}$, where $\boldsymbol{u}_{\mathrm{c}} = \boldsymbol{\Omega} \times \boldsymbol{r}$ is the corotation velocity, and the electric field becomes the corotational electric field, $\boldsymbol{E} = -(1/c)\boldsymbol{u}_{\mathrm{c}} \times \boldsymbol{B} \equiv \boldsymbol{E}_{\mathrm{c}}$, which is supported by the GJ charge density $\rho_{\mathrm{GJ}} = \nabla \cdot \boldsymbol{E}_{\mathrm{c}}/4\pi$. Near the star, the general relativistic effect changes the form of ρ_{GJ}, which in turn changes the acceleration field for a given current density. The corotational electric field has no component along the magnetic field, $E_{\|} = 0$.

Although the particles nearly follow the rigid field lines, ideal corotation is not realized everywhere in the inner magnetosphere. This is because the particle supply does not lead to the GJ density everywhere. Even a small deviation of the real charge density from the GJ charge density creates a field-aligned electric field. The unscreened electric force is balanced by an inertial force; oscillations (Langmuir type) can develop and, in some cases, a huge potential drop appears, which can be large enough for renewed electron-positron pair creation, depending on situations, e.g., imposed current density, field geometry, emission from the neutron star.

The nature of completely charge separated flows depends on field line curvature. The charge density of the flow varies according to the equation of continuity, $\rho_e = en \propto B/v$, and thereby once the flow is relativistic, the charge density varies in proportion to the magnetic field strength: $\rho_e \propto B$. On the other hand, the GJ density changes as $\rho_{\mathrm{GJ}} \propto B_{\mathrm{z}}$. Hence, even if the GJ density is realized somewhere in the flow, the charge density deviates from the GJ value and $E_{\|}$ should appear. On field lines curving toward the rotation axis, the ratio, $\rho_e/\rho_{\mathrm{GJ}} = B/B_{\mathrm{z}}$, decreases outwardly so that the charge tends to be depleted on these field lines. On field lines curving away from the rotation axis, the charge tends to exceed the GJ value. In some regions, when the flow is non-relativistic, the GJ density appears for a long distance by adjusting the velocity so as to screen the field-aligned electric field. Such a flow in general has spatial oscillation of the Langmuir type.

3. Outer Gap

3.1. Quasi-Static Consideration

The original idea of the outer gap is as follows (Holloway 1973). Suppose some particles are ripped off through the light cylinder due to the centrifugal force, wave pressure or whatever. Particles in the inner magnetosphere become insufficient to provide the GJ charge density. The density perturbation grows and the charge separation by the central dynamo is so strong that the region around the *null surface* where $\rho_{\mathrm{GJ}} = 0$ is left vacant with unscreened $E_{\|}$.

Refilling particles back through the l-c is unlikely because it opposes the emf. More likely, additional charges are provided by an electron-positron pair creation cascade in the gap, perhaps initiated by a cosmic ray in the gap. The created pairs are immediately charge-separated so as to refill the charge depleted regions. The gap will then be reduced. Furthermore, electrons going back to the star give negative charge to the star, and as a result the vacant space above the polar dome can even be refilled.

After all, the corotation region expands and occupies the space within the light cylinder as far as possible. The expansion of the corotation region may induce further loss of particles. More importantly, the refilling action produces an electric current system. It is outward across the outer gap and inward in higher latitudes, see Figure 1 (right). This current is completely consistent with that required by the wind. Thus it is indicated that the pair creation to refill the gap cooperates with the wind: the outer gap accelerator will operate in the loop current steadily. A bonus is for the wind to get the quasi-neutral plasmas via pair creation.

3.2. A Steady Outer Gap Model with Pair Creation

Hirotani & Shibata (1999a, 1999b, 1999c) calculated the electric field in a steady one-dimensional outer gap self-consistently with a gamma-ray distribution function and flows of electrons and positrons created by photon-photon collision. The gap is partially refilled, but still has a field-aligned electric field.

The gap model is somewhat similar to a semiconductor in the sense that the concept of holes and real charged particles is convenient. There are effectively positive holes to the left of the null surface, and negative holes to the right of the null surface in Fig. 1. The charge density of the holes is minus the GJ value, $-\rho_{\mathrm{GJ}}$. For example, on the left, if the positive holes are filled with electrons, then the real negative charge equals the GJ value and the field-aligned electric field can be screened out $\rho_e - \rho_{\mathrm{GJ}} = 0$. In the gap, two regions with oppositely charged holes are facing each other, and a field-aligned electric field appears.

Particles are accelerated in the gap and emit gamma-rays, which collide with soft photons to make pairs. The pairs are immediately separated in opposite directions. These pairs produce space charge in the gap so as to refill the gap in part. The field aligned electric field is weakened.

These processes are described by the Poisson equation, equations of motion, equations for the gamma-ray distribution function with source and sink terms, and equations of continuity for electrons and positrons again with a source term. HS solved these equations for a steady outer gap.

3.3. A Steady Outer Gap Model with external current sources

Conventional outer gap models assume that all the current carrying particles are created in the gap. However, external current-carrying particles may come into the gap: current-carrying electrons may come in from the wind, or positrons may be emitted from the stellar surface.

This external current supplies an additional space charge as if a back ground charge is added to the GJ charge density. As a result, the position of the outer gap moves inward or outward. In principle, the external-current-dominated outer gap can appear near the star. In this sense there is no obvious distinction between the outer gap and polar gap. The difference is just one parameter that is the ratio of the *external* current-carrying particles to the current-carrying particles *produced in the gap*. In contrast to the outer gap, conventional polar cap models assume a completely external current source.

4. Models of the inner magnetosphere

Let us summarize the various reactions of the inner magnetosphere to the imposed current. The inner magnetosphere through which electric current is forced to run can be classified according to the field line curvature and the direction of the current. The direction and intensity of the current on each field line are determined globally, and are more like quantities imposed by the wind at least for young pulsars.

The outer gap is located on field lines with away curvature and an outgoing current. As has been described in detail, a steady, pair-creating outer gap is possible. If the current running through the gap is all carried by electrons and positrons *created in the gap*, the gap is located at the null surface. If some part of current is carried by externally supplied particles, then the gap shifts its position, but the electrodynamics itself is the same as that which applies around the null surface.

As for the polar cap accelerators, on field lines curving 'toward' the rotation axis, the Arons type model is known (Scharlemann, Arons, & Fawley 1978; Arons, & Scharlemann 1979; Shibata 1997), where an external super GJ current is assumed to be a critical value. The region near the star is over-filled with negative charge, while the down stream region becomes charge-depleted due to field line curvature ($B/B_{\rm z}$ decreases). Therefore for these two regions, one needs positive charge and the other needs negative charge in order for the real charge density to adjust to the respective GJ values. Thus the electrodynamics of this accelerator is as same as the outer gap. The difference is that the polar gap current is externally supplied. The gap can make pairs, and some of the pairs contribute to the current so that the polar gap model can be modified with larger current densities than the critical value. In this case, one has a flux of backward positrons.

However, if the current density required by the wind is smaller than a certain value, the flow is an oscillatory GJ flow without any acceleration (Shibata 1997).

Acceleration takes place also on field lines curved away from the rotation axis. In this case, again the electrons are assumed to flow out. Even if the flow is initially an oscillatory GJ flow near the star, as the flow goes up, *the*

space automatically becomes over-filled at some distance because of the field line curvature (B/B_z increases). This catastrophic break up of an $\boldsymbol{E}\cdot\boldsymbol{B} = 0$ condition may be terminated by forming a positive charge region downstream. This is possible by polarization of a pair plasma. Electrons are accelerated to emit gamma-rays and subsequently to make pairs. Pair positrons are decelerated, and as a result positive space charge appears.

However, pair creation rate for this screening to operate is much higher than the value expected by the normal magnetic pair creation: the simple idea that once the pair density exceeds the GJ density, the field-aligned electric field is immediately screened out is not correct (Shibata, Miyazaki, & Takahara 1998). The reaction of the away curved field lines to the imposed current has yet to be clarified.

5. Future

As seen above, the inner magnetosphere reacts to the imposed current in various ways depending on current direction, current density, field geometry, external particle flux, and so on. The accelerators can appear at various altitudes, so there is no clear discrimination between the outer gap and the polar gap. This might be confirmed observationally by the identification of various new pulse components. We need more accurate local models of the field-aligned accelerators, which should predict the properties of the high energy emission. The local models should have adjustable free parameters, such as current density and external particle flux, and should be self-consistent in the sense that the electric field, the pair production process, the photon distribution and motion of the particles are all solved together. Such sophisticated models can only interpret detailed observations giving phase (component) resolved energy spectra.

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